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SOME CONCLUSIONS BASED ON THE STUDY OF
MULTI-STATE FLUID LOGIC ELEMENTS

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RESEARCH AND DEVELOPMENT
IN
FLUID LOGIC ELEMENTS

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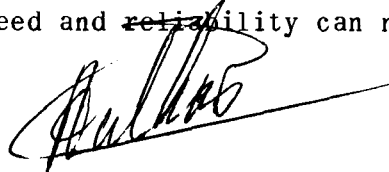
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DATE: AUGUST 10, 1964

ABSTRACT

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A brief historical analysis shows how the development of pure fluid digital logic elements has followed a pattern. Attention was first centered on gain, then on reliability and lastly on speed. A conflict between gain and speed is now developing, and it appears that to resolve this conflict, while preserving reliability, sacrifices in gain will need to be made. An element which makes more effective use of the control jet shows promise of providing a solution to the speed-gain dilemma. The UNIVAC inverter employs control jet reaction in order to reduce its dependence on wall attraction; however, the NASA contract to develop multi-state elements has shown the importance of reducing the effect of wall attraction still further. By utilizing elements with lower gain in conjunction with multi-state elements UNIVAC feels that rapid improvements in speed and ~~reliability~~ can now be achieved.

A handwritten signature in black ink, appearing to be "A. L. H. B.", is written over the end of the abstract text.

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INTRODUCTION

Fluid amplifiers have not yet fulfilled all their early promises. This analysis aims to demonstrate that because the development of fluid logic was preceded by electronics many of the sound postulates made in the electronics field have been allowed into the fluids field without an adequate appraisal. The unfortunate result of this practice is that many researchers have been led to believe that one of the most important properties of a digital fluid logic element is high gain.

Not until work was carried out in the field of multi-state fluid logic elements was it demonstrated that elements which depend for their high gain on either wall attachment or turbulence are necessarily at least an order of magnitude slower than elements which do not rely on these effects.

The introductory analysis may be an over-simplification of the historic development of the fluid amplifier art. Its principal merit is that it does fit the known facts and does offer the prospect of a major breakthrough for digital fluid devices.

The discussion of present applications describes some of the industrial uses of digital fluid devices. An evaluation of the design philosophy of fluid amplifiers shows that insufficient interest has been given to the speed problem in digital fluid logic. Theoretical analyses have failed to suggest really fruitful solutions to this problem and it appears that speed can be achieved only at the expense of gain. The reaction amplifier is shown to make more effective use of the control signal and therefore depends less heavily on wall attraction to achieve a specified gain. This element is easily handled analytically and offers promise of a major breakthrough in speed.

The remarks on the future of fluid elements predict a trend toward miniaturized low gain elements with low aspect ratios, and a diminishing reliance on wall attachment effects.

A theoretical treatment for momentum exchange and control jet reaction devices is described. Because of the elementary principles employed by these devices, relatively crude yet practical theory can be applied with reasonable accuracy.

PART 1 - THE DEVELOPMENT OF DIGITAL FLUID AMPLIFIERS

1.1 Historical Analysis

The spark which ignited the explosive field of fluid amplifiers was supplied by the Diamond Ordnance Fuze Laboratories in 1960 with the announcement of a fluid amplifier which uses no moving parts.

At first it appeared that the new fluid amplifier would fill a wide void between the slow mechanical devices used in control equipment and calculating machines and the unnecessarily fast and expensive electronic devices used in high speed computers.

Initially, progress seemed rapid and many inventions appeared and hundreds of papers were written on fluid amplifiers. It was found that fluid amplifiers could be tailored to give an almost unlimited variety of D.C. characteristics. Many problems, involving the interconnections of complex circuits, were encountered and systemically solved.

About two years later Raymond N. Auger¹ showed the importance of input and output isolation by demonstrating the ease with which his turbulence amplifiers could be interconnected. It now appeared that all circuit problems had been solved, and that the only remaining problems were speed improvement and fabrication.

The turbulence amplifier had two major disadvantages; it could not be fabricated as cheaply as would have been desired, and it was slow to recover its full output signal strength once the control signal had been removed.

When the initial results of early fluid amplifier investigations were announced, evaluations made by UNIVAC engineers disclosed the serious high-speed limitations of pure fluid digital devices. It later appeared that fluid devices were not even as fast as mechanical devices. UNIVAC had been investigating the feasibility of using fluid devices to control magnetic tape by switching air between two counter-rotating capstans. Electromechanical valves has already been developed which could switch in less than half a millisecond. It was felt that by eliminating moving parts altogether even higher speeds could be obtained. Early tests carried out by UNIVAC showed that the switching time of the pure fluid flip-flop was approximately one millisecond.

A comprehensive program was then established to develop a high-speed pure fluid logic device. An entirely new concept, employing the "edgetone" effect, was conceived, and a device was built whose aim was to achieve speeds comparable to the half-period of the edgetone frequency. This device showed that speeds could be improved, and that an understanding of the basic edgetone phenomenon could lead to a useful high-speed element. Because the edgetone phenomenon is extremely complicated, several mathematical and theoretical studies are presently underway to clarify the directions for future development.

A parallel effort in the quest for higher speeds in fluid devices resulted in the UNIVAC inverter. This device achieved a switching speed of about a third of a millisecond; its chief characteristics being the increased effectiveness of the control signal, and, consequently, a reduced dependence on wall lock-on effects. Although this speed increase was not dramatic, it did point the way to a promising means of improving fluid amplifier performance. A further step towards a useful high speed device was the building of a NOR gate. This was achieved by marrying a four input OR gate to the UNIVAC inverter. The design of the OR gate was such that complete isolation of all four inputs was achieved. The gain of the inverter was sufficient to permit each NOR gate to drive four other NOR gates, and the inverter was found to be sufficiently insensitive to output load that no problems were encountered in assembling complex circuits.

Unfortunately, the addition of the four input OR gate to the inverter increased the switching time of the resulting NOR gate to almost one millisecond, and it appeared that we had made little progress in terms of speed. Progress in other areas such as fabrication, experimental and analytical techniques and design philosophy was being made but speed remained a major difficulty.

Early in 1963 NASA conceived the idea that perhaps our approach should be centered less around the performance of binary devices, which owed their popularity to working principles in computer electronics, and more around multi-state devices using the altogether different principles of operation made possible by the unique properties of interacting jets enclosed by walls.

Multi-state elements proved more difficult to design than had been anticipated. Most of the early attempts resulted in devices whose steady-state characteristics failed to meet even the barest design specifications. It soon became clear that the difficulties which had been encountered in designing a satisfactory flip-flop were compounded in the design of a tri-stable element.

Logical design studies in multi-state elements showed that although a tri-stable element had an advantage over more conventional elements in the design of an asynchronous shift register its use in general was limited. A more useful device would be a tri-level element which could enhance the use of the more logically powerful ternary arithmetic and its associated algebra. The UNIVAC aerosonic device was known to be capable of producing three different output levels depending on its control signals and it was felt that this device might form the basis of a useful three-level element. Tests carried out on this element showed that while three-level operation was extremely sensitive to small geometry variations three-state operation could easily be obtained by simply replacing the central splitter responsible for the edgetone by a receiver to form a third output. UNIVAC now had a three-state element with limited logical utility.

Several three-state elements were built and an asynchronous shift register was assembled² using these elements in conjunction with NOR gates. Dynamic tests showed, however, that the three-state element was even slower than the conventional flip-flop, and the search for a new principle of operation continued.

The switching speeds of active elements appeared to be of the order of one millisecond for a power nozzle width of .020 inches, however, tests on passive elements employing momentum exchange showed that speeds could be reduced to one tenth of a millisecond, if the wall attachment effects were eliminated. This discovery lead to the development of two multi-state logic elements whose operation depended only on the exchange of momentum between the input jets. It soon became evident that the speed of a fluid logic circuit depended almost as much on the amount of logic which could be accomplished at each jet interaction region as on the speed of the individual elements.

We are at the crossroads in fluid amplifier development; on the one hand we have elements with very high gain and poor switching speed and on the other we have elements with very high switching speed and poor gain. By tradition the former elements have been classed as active while the latter have been classed as passive but in the light of recent discoveries, this distinction has become less meaningful.

What is now anticipated is a synthesis of active and passive principles such that high speed is combined with adequate gain.

1.2 Present Applications of Pure Fluid Digital Devices

Application of a new idea rarely waits for the idea to be perfected. Pure fluid logic elements have far to go before anything like optimum designs are achieved, yet even in their present state they have found industrial uses as timing and control devices. Elements have been designed which use very little power, are quiet, and can operate on conventional shop air under almost any conditions of temperature, noise, vibration, humidity and shock.

UNIVAC has built a timing device for the Sandia Corporation and a small computer for demonstration purposes using the UNIVAC pure fluid NOR gate. A paper announcing FLODAC, the world's first pure fluid digital computer, is to be presented at the Western Joint Computer Conference in San Francisco this Fall, and it is anticipated that this significant paper will herald a new era in man's use of fluids.

At present many problems which can be solved by means of electromagnetic relays can be solved more cheaply and reliably by means of fluid amplifiers.

1.3 Trends in Digital Fluid Logic

The success of fluid amplifiers will probably lead to many applications unheard of today. Such applications as garage doors which open at the sound of a particular car horn, industrial counting and checking devices, telephone relays, and automatic TV channel selectors, capable of responding to a voice input will almost certainly materialize within ten years.

UNIVAC expects to develop elements which are fast enough to do fairly sophisticated computer logic. These elements will be sufficiently inexpensive to justify the extended use of parallel logic in performing operations hitherto regarded as lying in the domain of electronics. Mechanical and electromechanical logic elements will become a rarity since they will, in general, be replaced by fluid devices. Hole, ripple and bump detectors, such as those used in paper tape readers, will probably use air both as a means of detecting information and as the medium for pure fluid logic decoding and error detection circuits.

PART 2 - THE DESIGN PHILOSOPHY OF FLUID AMPLIFIERS

2.1 The Wall Effect

A two dimensional jet of fluid directed close to a wall will tend to be drawn toward it. This is called wall attraction and is the basic mechanism underlying the operation of the flip-flop developed by the Harry Diamond Laboratories. The reason for a wall was to increase the angle through which the power jet could be deflected, and thus improve the gain.

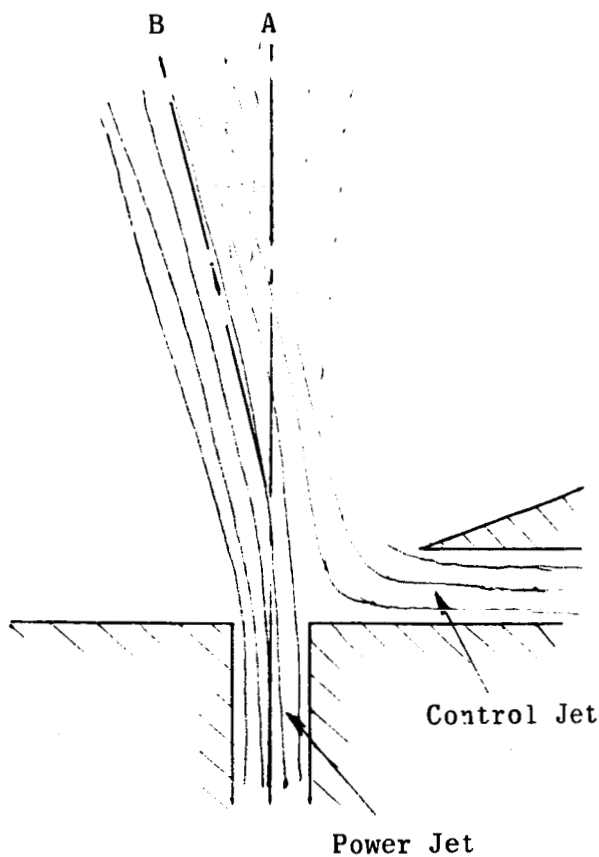


Figure 1(a)

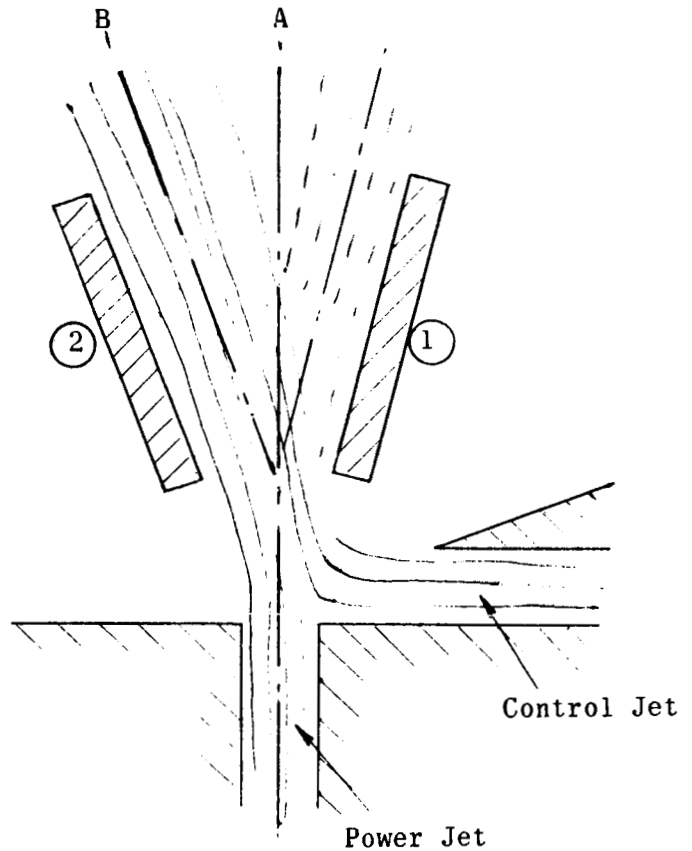


Figure 1(b)

Figure 1(a) shows a power jet being acted on by a control jet. The undeflected position of the jet centerline is shown by line A and the deflected position by line B.

Figure 1(b) shows the same power jet being acted on by the combined effect of the control jet and walls (1) and (2). Wall (1) attracts the power jet to the right of the centerline when no signal is present, while wall (2) attracts

the power jet to the left when the control signal is present. It is clear that the presence of walls (1) and (2) can increase the effectiveness of the control jet by amplifying the angular deflection which would have been produced by the control jet in the absence of walls.

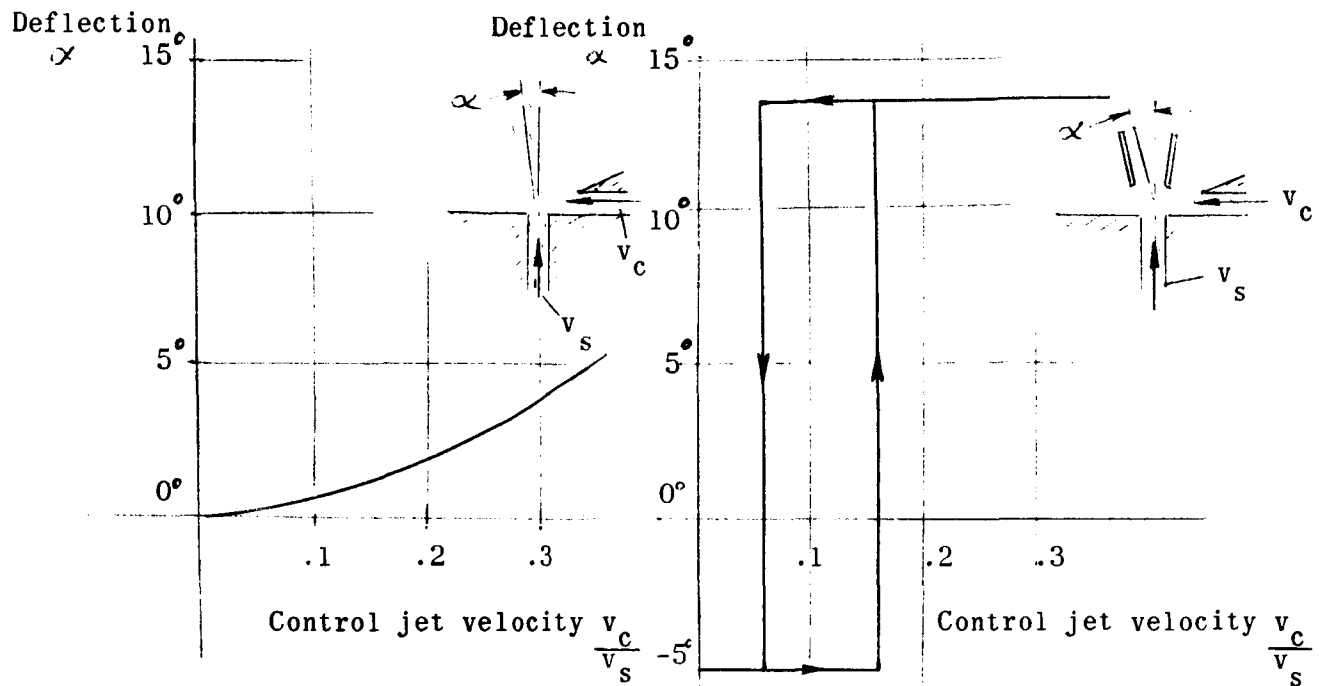


Figure 2(a)

Figure 2(b)

Figure 2(a) shows the relationship between the angle of deflection of a constant power jet plotted against the control jet velocity when no walls are present, while Figure 2(b) shows the relationship between the same two variables after walls have been added. We note that a drastic change in the performance of the device results from the addition of the walls, and that much greater deflections can be realized when walls are provided.

From the point of view of steady-state performance it is clearly an advantage to use walls because greater control jet effectiveness can be achieved by this means. If we now consider the frequency response characteristics, the picture is not so clear. The hysteresis supplied by the walls produces a phase difference between an alternating input control flow and the output deflection

angle α . When the phase angle becomes too large the power jet is unable to follow the control jet and remains locked on one of the two walls, whereas with no walls the power jet responds to the control jet at all practical frequencies.

It appears that the use of walls to achieve gain results in a slower element, therefore, other methods of achieving greater control signal effectiveness should be sought.

2.2 The Turbulence Amplification Principle

A laminar stream traversing an open space from a nozzle to a receiver can be broken down by means of an extremely small disturbance.

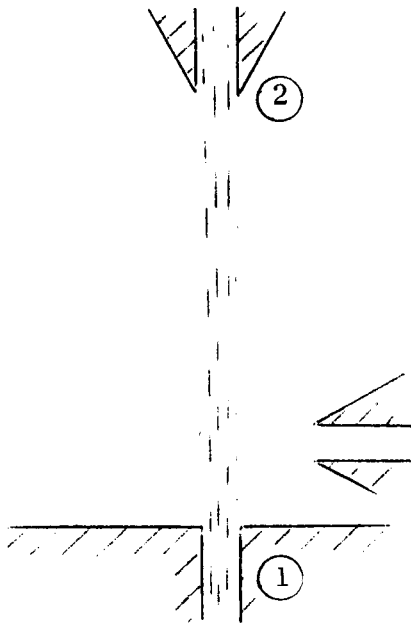


Figure 2(a)

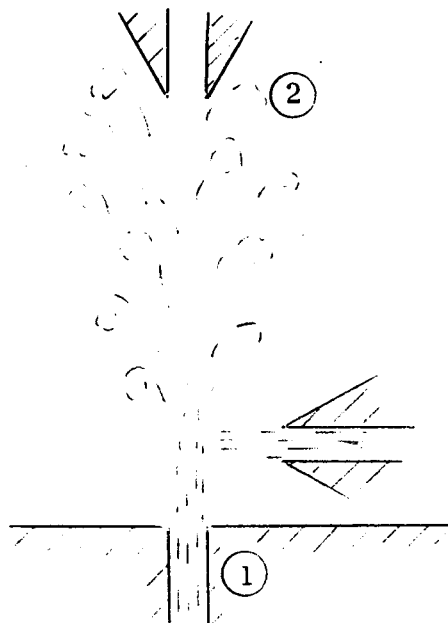


Figure 2(b)

Figure 2(a) shows a laminar power stream being discharged from a nozzle (1) into undisturbed air and being picked up by receiver (2). Figure 2(b) shows how a control stream has broken down the laminar power stream into a rapidly diverging turbulent stream, the energy in which has been almost totally dissipated as eddies before reaching the receiver. This device is capable of operating as an inverter with very high gain.

If a number of control nozzles are directed toward the base of the laminar power stream we have a NOR gate with complete input and output isolation. Fan-in and fan-out capabilities of at least four are easily obtained, and further development of these principles shows great promise. Although their speed will be improved by miniaturization, these elements suffer from a built-in handicap. To ensure adequate dissipation of turbulent energy in the power stream when the control signal is applied, the distance between the power nozzle and the receiver, expressed in nozzle diameters, must be much larger than with

other types of fluid amplifiers. This leads to a further difficulty; when the control jet is turned off the existing turbulent energy in the region of the receiver delays the recovery of laminar flow so that the turn-on time is almost an order of magnitude slower than the turn-off time.

2.3 Control Jet Reaction

The conventional method of introducing a control signal is to convert slow moving air at the control signal pressure p_c to fast moving air at the ambient pressure p_o , and allow the fast moving control stream to impinge against the fast moving power stream. Because momentum is conserved, the power stream is deflected through an angle α as shown in Figure 3(a). A more effective method of introducing a control signal is to allow the static pressure p_c of the control signal to act on one side of the power jet, and to permit some of the control air to accelerate along a path parallel to the power jet as shown in Figure 3(b).

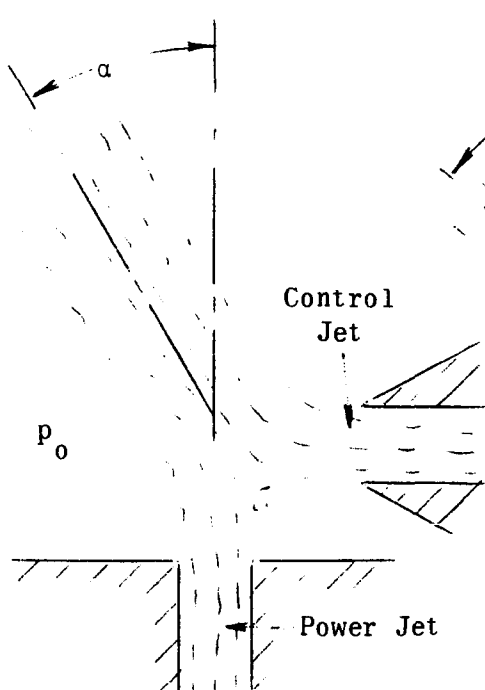


Figure 3(a)

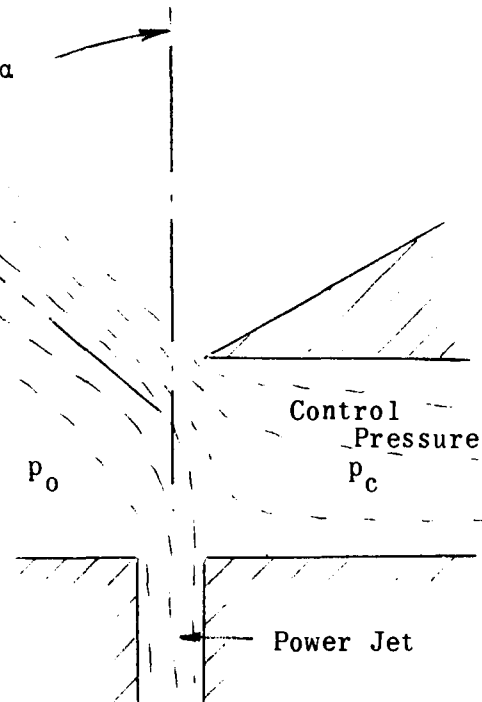


Figure 3(b)

Based on principles to be discussed in Part 4, theoretical analyses of both types of free jet amplifiers show satisfactory agreement with experimental results. Both theory and experiment have shown that greater deflection angles α are possible using control jet reaction than using momentum exchange. In addition to this advantage less energy is destroyed as a result of the jet interaction.

The UNIVAC inverter used the control jet reaction principle together with some wall attraction. The wall was necessary in order to obtain the fan-in and fan-out requirements, but it resulted in a speed penalty. What is, therefore, needed is a device which does not depend on wall attraction but which has adequate gain for digital logic circuits.

PART 3 - THE FUTURE OF DIGITAL FLUID AMPLIFIERS

3.1 The Need for a Workable Theory

Any study whose aim is a recognizable product benefits when a set of ground rules and a working theory are established. Many studies such as alchemy and astrology were held back primarily because they appealed to authority rather than to the scientific scrutiny which demands that their logic be demonstrated by means of a mathematical model.

The most dramatic advances in science have been made in areas where theory is not only advanced but usable. In some fields such as the theory of structures, the end product shows a preference for mathematical simplicity as typified by the suspension bridge rather than the statically indeterminate structures of a bygone age. Even in aerodynamics, complex theory has been replaced by the simplifying approximations made necessary by an aesthetic demand for the mathematically obvious.

At UNIVAC we have learned the importance of being able to calculate the performance of our fluid elements before building them.

Work on company sponsored projects, and on contracts awarded by the Harry Diamond Laboratories⁸, the Sandia Corporation and NASA have shown that without analytical tools, progress in developing fast fluid logic elements is likely to be slow. The NASA contract was aimed partly at overcoming the speed limitations by using more logically powerful fluid devices. Tests showed that multi-state memory elements were even slower than conventional flip-flops and that multi-level elements were impractical. The only elements which showed real promise were those multi-state logic elements which did not rely on wall attraction. Fortunately, these elements could be treated analytically using very basic fluid mechanics, and it was agreed that we should spend most of our time studying this type of element and the logic concepts involved.

Mathematical studies have shown that it is possible to predict the performance of a low-gain element whose speed is many times that of conventional fluid logic elements. In keeping with our belief that elements for which good

mathematical models exist are in general to be preferred to those for which only a vast body of experimental data exist, UNIVAC proposes that a study of the reaction amplifier be carried out. This element has adequate gain for digital logic and its performance under steady state and transient conditions appears completely predictable. At present it is the only element for which a mathematical theory shows promise of being both accurate and practical.

3.2 Trends in Fluid Element Design

The three main requirements to be satisfied by digital fluid logic elements are:

- 1.) Low power
- 2.) High speed
- 3.) Insensitivity to small geometric variations

Low power places a premium on low aspect ratio and demands that elements be capable of operating at low Reynolds numbers.

High speed demands that elements be extremely small and that phenomena which depend on the building up or breaking down of boundary layers or on the creation and destruction of laminar flow should not be used.

Insensitivity to small geometric variations makes it inadvisable to attempt to design high gain devices which depend for their performance on the critical placement of walls or wedges.

The only known element, which does not depend on either walls or laminar breakdown yet has adequate gain for digital logic circuits, is the reaction amplifier. Attempts to improve fluid logic elements will probably show a trend toward elements employing the principles of control jet reaction.

Low Reynolds number operation and low gain devices make desirable the use of multi-state logic elements such as those developed under this contract. The logical design rules for use with these elements require that each multi-state element be both preceded and followed by a control jet reaction element.

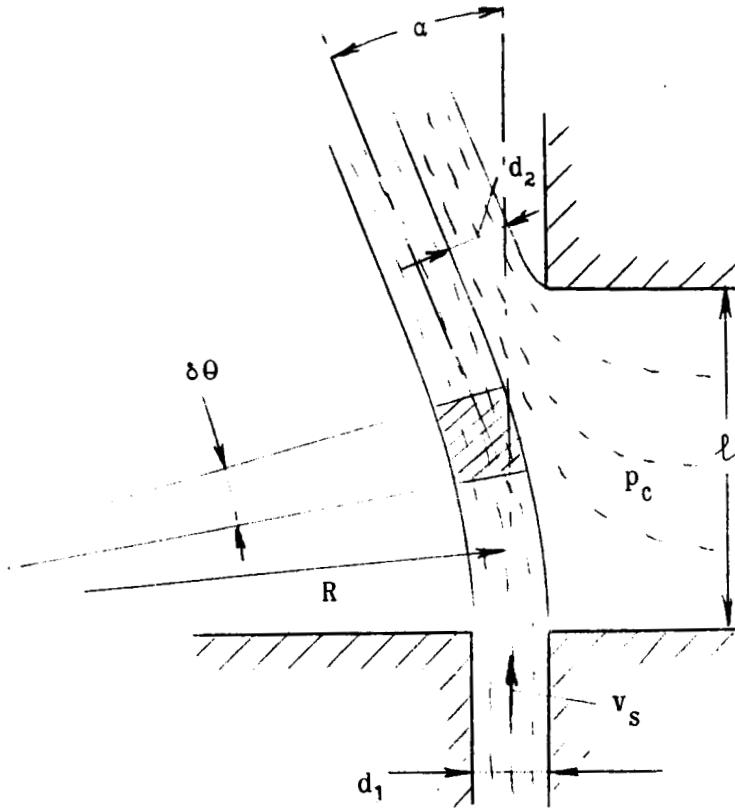
It might at first appear that the limited fan-in and fan-out capabilities of low gain elements would result in much cascading of elements. Although this is true, it should be remembered that an element is nothing more than a jet interaction region, and in an integrated package, these regions can be packed extremely close together. Also the multi-state elements will result in some simplification of the logical design and will partially offset the need for cascading elements.

A further objection to the use of low gain elements might be that since more low gain elements would be required to perform a specified logical function,

more power would be needed by a circuit employing these elements than by a circuit employing high gain elements. This objection is not valid because low gain elements can be designed to function satisfactorily at much lower Reynolds numbers than high gain elements. Indeed, it is the extremely low Reynolds number operation of the low gain elements that opens the way to rapid advances in digital fluid logic systems.

PART 4 - A THEORETICAL FOUNDATION FOR FLUID LOGIC ELEMENTS

4.1 Steady-State Analysis



We shall assume that the pressure p_c acts on the side of the supply jet as shown in Figure 4, and that the momentum imparted by the control fluid is negligible.

Let the other side of the jet be exposed to atmospheric pressure, then equating inertia and pressure forces acting on an element of the supply jet, and assuming unit depth, we have:

Figure 4

Inertia force = Pressure force

$\therefore \text{Mass} \times \text{centripetal acceleration} = \text{Pressure} \times \text{Area}$

$$(\rho d_1 R \delta \theta) \left(\frac{v_s^2}{R} \right) = (p_c) (R \delta \theta)$$

$$R = \frac{\rho d_1 v_s^2}{p_c}$$

(1)

Where

R is the mean radius of curvature of the deflected supply jet,
 d_1 is the supply jet nozzle width,
 ρ is the fluid density, and
 v_s is the supply jet velocity.

The effective width of the control nozzle is d_2 as shown in Figure 4. If this width is specified, and p_c is known, the length ℓ and the supply jet deflection angle α may be calculated by first using formula (1) to determine the radius of curvature of the jet then applying the rules of elementary trigonometry to specify completely the geometry of the interaction region.

A comparison between a momentum exchange amplifier and a control jet reaction amplifier was carried out by analysis, using the following input specifications:

Effective power nozzle width	=	d_1
Effective control nozzle width d_2	=	d_1
Power supply total pressure	=	p_s
Control input total pressure p_c	=	$.5p_s$

Calculations showed that:

Deflection angle α_m using a momentum exchange device	=	26.5°
Deflection angle α_c using a control reaction device	=	35°

The ratio α_c/α_m for a pressure gain of 2 is therefore,

$$\frac{35}{26.5} = 1.32$$

Theoretically the ratio α_c/α_m increases rapidly as the pressure gain increases. For a pressure gain of 10 the ratio α_c/α_m is 3.05. This means that for higher pressure gains control jet reaction produces several times the deflection produced by momentum exchange. In addition to this advantage less energy is destroyed and therefore greater energy is recoverable when the control jet reaction principle is employed.

4.2 Transient Response

The response of fluid amplifiers, utilizing either wall effects or turbulence, to a suddenly applied control signal has always been difficult to analyse theoretically because the complex aerodynamic principles on which these elements depend are improperly understood. Schlichting⁴ has studied non-steady boundary layers and the development of turbulence and has shown that an analytical treatment which does not take into account all the terms in the general three-dimensional Navier-Stokes equations is at best only a crude approximation for high Reynolds numbers. For low values no analytical approach has yet been devised, although large scientific computers can now solve numerically a simplified two-dimensional approximation; even so the value of this approach has not yet been demonstrated.

Tests carried out on high gain devices have shown that switching times are invariably slower than might be expected on the basis of molecular transport times. It is certain therefore that the destruction of a boundary layer or the re-establishment of laminar flow is a time-consuming effect which is likely to prove insurmountable even when the aerodynamics are completely understood.

In contrast to the complexities introduced by high gain elements, tests carried out on momentum exchange devices show that very elementary theory is involved in determining switching times with reasonable accuracy.

As an example let us calculate the switching time of a low gain momentum or reaction type element operating on air at a power supply pressure of 20 inches of water. Let the distance from the nozzle to the receiver be .050 inches. Then the switching time in response to a step input may be calculated as follows:

$$\text{Switching time} = \frac{\text{distance from nozzle to receiver}}{\text{velocity of air leaving nozzle}}$$

Air discharging into the atmosphere under a supply pressure of 20 inches of water leaves the nozzle with a velocity of approximately 300 feet per second.

Thus:

$$\begin{aligned}\text{Switching time} &= \frac{.050}{12 \times 300} \text{ seconds} \\ &= 13.9 \text{ microseconds}\end{aligned}$$

This speed is several orders of magnitude faster than has been obtained with high gain devices, and should result in a re-evaluation of the possible applications of pure fluid logic elements.

Because control jet reaction devices do not depend on sensitive boundary or turbulence effects it is expected that switching times for these elements will be of the same order as for momentum exchange devices, and will show comparable agreement between theory and experiment.

Submitted by: Trevor D. Reader
Trevor D. Reader, Project Engineer

TDR/jo
8/10/64

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